# PERFORMANCE OF AN ALUMINA BALL PACKED BED POROUS MEDIA BURNER FUELED BY PRODUCER GAS

**by**

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**Thesis submitted in fulfillment of the requirements**
**for the degree of**
**Master of Science**

**April 2012**

## ACKNOWLEDGEMENTS

First of all, I wish to uphold my greatest gratitude and praise to Almighty God for His grace, blessing and guidance throughout the whole process of this research project. May all the glory and honour be unto Him forever and ever.

I wish to express my utmost gratitude to my supervisor, Professor Dr. Zainal Alimuddin bin Zainal Alauddin for his relentless care, advice and guidance through the while project. There were times of difficulties in the midst of project. But he is always willing to share his precious experience to encourage me to march forward. It is my greatest honour to have the opportunity to work together with him.

Other than that, I would like to thank all the technical staff for assisting me with their experience, especially in the process of design and fabrication. I would like to specially thank Mr. Abdul Hamid, Mr. Khomaruddin and Mr. Zalmi for their support and guidance.

Also, I wish to thank my postgraduate colleagues in Biomass and Bioenergy Laboratory especially, Mr. Khaled, Mr. Yow, Mr. Ahmed and Mr. Ikhwan for their help and valuable experience. It is truly pleasure to be able to work together with them and share the down time and joyful moment together.

I would like to thank Universiti Sains Malaysia (USM) for approving my Fellowship Scheme and Postgraduate Research Grant Scheme to support me for the whole research work in USM.

Last but not least, I wish to thank my father and my sibling for supporting me to continue pursuing my master degree. I am grateful for their prayer and blessing to me.

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| | |
|---|---|
| $Al_2O_3$ | Alumina |
| CB | Cyclone burner |
| $CH_4$ | Methane |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| CV | Calorific value |
| Exp. | Experiment |
| FeCrAlY | Iron-chromium-aluminium-yttria alloy |
| GC | Gas chromatograph |
| $H_2$ | Hydrogen |
| $H_2O$ | Water |
| HEX | Heat exchanger |
| HHV | High heating value |
| LCV | Low-calorific-value |
| LHV | Low heating value |
| LPG | Liquefied petroleum gas |
| LPM | Liter per minute |
| MSB | Matrix stabilised burner |
| $N_2$ | Nitrogen |
| $NO_x$ | Oxides of nitrogen |
| PCC | Pressurized cyclone combustor |
| Pe | Peclet number |
| PG | Producer gas |
| PMB | Porous media burner |
| ppcm | Pore per centimeter |
| ppm | Part per million |
| PSZ | Partially stabilised zirconia |
| PVC | Precessing vortex core |
| RE | Reynolds number |
| RFB | Reciprocal flow burner |
| RFZ | Recirculation flow zone |

| | |
|---|---|
| RSCP | Reciprocating Superadiabatic Combustion Porous Media Burner |
| SiC | Silicon carbide |
| $SO_2$ | Sulphur dioxide |
| Sr | Strouhal number |
| SSB | Surface stabilised burner |
| TCD | Thermal conductivity detector |
| YZA | Yttria-stabilised zirconia/alumina |
| ZTM | Zirconia-toughened mullite |

## LIST OF SYMBOLS

| | |
|---|---|
| $\Phi$ | Equivalence ratio |
| H | Height of second layer packed bed |
| $T_f$ | Final temperature |
| $T_o$ | Initial temperature |
| $Q_c$ | The heat release by chemical energy conversion |
| $Q_a$ | Energy added from solid |
| $H_f$ | Enthalpy of fluid |
| $H_0$ | Enthalpy of solid |
| $S_L$ | Free laminar flame speed |
| $d_m$ | Equivalent pore diameter |
| $c_p$ | Specific heat of air |
| $\rho_g$ | Density of gas |
| $\lambda_g$ | Thermal conductivity of gas |
| $G_\phi$ | Axial flux of angular momentum of swirl |
| $G_x$ | Axial flux of linear momentum |
| $D_e$ | Exit diameter of burner |
| S | Swirl number |
| $r_e$ | Nozzle radius at the exit of the burner |
| $r_i$ | Effective radius at the middle of the inlet pipe |
| $A_\varepsilon$ | Inlet area |
| $n_{H_2}$ | Mole fraction of hydrogen |
| $n_{CO}$ | Mole fraction of carbon monoxide |
| $n_{CH_4}$ | Mole fraction of methane |
| $\rho$ | Density |
| $C_f$ | Flow coefficient |
| Ao | Area of orifice hole |
| $(P_1 - P_2)$ | Pressure difference of orifice meter measured by digital manometer |
| $C_d$ | Coefficient of discharge of orifice meter |
| $\beta$ | Ratio of orifice hole diameter to pipe diameter |
| $\dot{m}$ | Mass flow rate |

| | |
|---|---|
| $\dot{m}_a$ | Mass flow rate of air into the shell of heat exchanger |
| $\dot{V}$ | Volume flow rate |
| $\eta_G$ | Efficiency of gasifier |
| $Q_{PG}$ | Output power of gasifier |
| $Q_{wood}$ | Input power of gasifier |
| $\eta_H$ | Efficiency of PMB-heat exchanger system |
| $\eta_o$ | Overall efficiency |
| $\epsilon$ | Effectiveness of heat exchanger |
| $T_{hi}$ | Inlet temperature of the exhaust gas |
| $T_{ho}$ | Outlet temperature of the exhaust gas |
| $T_{ci}$ | Inlet temperature of the cold gas into the heat exchanger |

**PRESTASI PEMBAKAR BAHANTARA BERLIANG JENIS LAPISAN TERPADAT BOLA ALUMINA DENGAN MENGGUNAKAN GAS PENGELUAR SEBAGAI BAHAN API**

## ABSTRAK

Gas kalori rendah dari pengegasan biojisim (Gas pengeluar) tidak dapat dibakar dengan kecekapan tinggi dalam pembakar biasa. Hal ini adalah disebabkan oleh karbon monosida (CO) yang terdiri daripada 20% dalam composisi gas pengeluar mempunyai halaju pembakaran rendah. Oleh demikian, CO memerlukan masa mastautin yang lebih panjang untuk pembakaran. Pembakar bahantara berliang (PBB) merupakan teknologi yang berprospek dalam usaha perbaikan prestasi pembakar untuk menyelesaikan masalah tersebut. Penyelidikan ini bertujuan untuk mengkaji prestasi PBB dengan menggunakan gas pengeluar sebagai bahan api. Satu pengegas bebas bawah terstrata telah digunakan untuk menghasilkan gas pengeluar dengan nilai pemanasan 4-5 $MJm^{-3}$. Satu PBB dua-lapis dengan lapisan terpadat pertama dan lapisan kedua yang terdiri daripada bola alumina 10 mm dan 20 mm masing-masing telah diselidik. Kajian ini dilaksanakan dengan pelbagai nisbah kesetaraan dan ketinggian lapisan terpadat kedua. Kadar aliran gas pengeluar adalah dimalarkan pada 130 LPM. Kadar aliran udara diubah-ubahkan untuk menghasilkan nisbah kesetaraan yang berbeza.

Suhu maksimum dan isipadu zon pembakaran meningkat dengan nisbah kesetaraan dan ketinggian lapisan terpadat kedua. Suhu maksimum terangkum antara 1300 K dan 1550 K untuk kesemua kes. Emisi CO berkurangan dengan nisbah kesetaraan dan meningkat pada nisbah kesetaraan yang amat rendah. Emisi oksida

nitrogen ($NO_x$) meningkat pada ketinggian lapisan kedua melebihi 140 mm. Emisi CO dan $NO_x$ minimum ialah 6 ppm dan 230 ppm masing-masing. PBB dengan ketinggian lapisan terpadat kedua 140 mm memberikan keputusan yang tebaik dalam configurasi ini dengan keupayaan untuk beroperasi dalam julat nisbah kesetaraan antara 0.33 dan 0.71.

Sebuah pembakar siklon (PS) telah dieksperimen dan dibandingkan dengan PBB dengan kadar aliran isipadu gas pengeluar yang sama pada 130 LPM. PS menghasilkan suhu maksimum pada 1200 K dengan emisi minimum CO dan $NO_x$ 4 ppm dan 350 ppm masing-masing. Prestasi PBB adalah lebih baik berbanding dengan PS. Dengan itu, sebuah penukar haba kelompang dan tiub telah disepadukan dengan PBB untuk penghasilkan udara panas dengan output termal maksimum 7 kW. Secara keseluruhannya, prestasi PBB adalah lebih baik pada nisbah kesetaraan rendah.

**PERFORMANCE OF AN ALUMINA BALLS PACKED BED POROUS MEDIA BURNER FUELED BY PRODUCER GAS**

## ABSTRACT

Producer gas from biomass gasification is unable to burn efficiently in conventional burner due to low burning velocity of CO which comprises of about 20% of the producer gas. Porous media burner (PMB) is a promising technology for improving combustor performance that could solve the problem. The study aims to investigate the performance of PMB fueled by producer gas from biomass gasification. A stratified throatless downdraft gasifier was used to generate producer gas with heating value of about 4-5 MJ $m^{-3}$. Investigation has been done on a 2-layer alumina balls packed bed PMB with first and second layer consist of 10 mm and 20 mm alumina balls respectively. The study was done at various equivalence ratios (Φ) and heights of second layer packed bed (H). Flow rate of producer gas was kept constant at 130 LPM whereas flow rate of air was varied to produce different equivalence ratios.

Increase in both equivalence ratio and height of second layer packed bed increase the maximum temperature and the volume of combustion zone. The combustion region achieved the highest temperature between 1300 K and 1550 K for all cases. CO emission generally decreases with equivalence ratio. $NO_x$ emission increases significantly when packed bed height exceeds 140 mm. But for the case of packed bed heights of 80 mm and 110 mm, it shows increasing CO emission near the lean limit. The lowest recorded emissions from the PMB were 6 ppm and 230 ppm for CO and $NO_x$ respectively. PMB with second layer height of 140 mm was found

to be the best height for the current setup that manages to operate with submerged flame between the range of equivalence ratio of 0.33 and 0.71.

A cyclone burner (CB) was experimented and the results were compared with the PMB for the same producer gas flow rate of 130 LPM. It produces lower maximum temperature at about 1200 K with minimum emissions of CO and $NO_x$ at 4 ppm and 350 ppm respectively. It was found that PMB has better performance than CB in general. A shell and tube heat exchanger was incorporated with the PMB for hot air production yielding maximum thermal output of 7 kW. Lean combustion in PMB generally yields better performance.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Vast and rapid development of technology to increase comfort and convenience to human being started since Industrial Revolution in 18$^{th}$ and 19$^{th}$ century. Industrial Revolution has catalysed the modernisation in technologies, changing the socioeconomic and cultural condition of many countries. Development of technology requires significant energy sources, especially electricity and fuel.

Human uses fuel since early human civilisation. Branches from trees are used to produce fire for lighting, heat to keep warm and protect themselves from wild animals. Also, heat from fire is used to keep them warm. Later, fossil fuel such as petroleum, natural gas, and coal were discovered. The capability of the fossil fuel to be processed into different derivatives with high heat content drives people to design equipment that manage to operate with these fuels. Consequently, the technology advancement has catalysed industrialisation and economic revival which improves the lifestyle and bring a lot of convenience to people, especially those staying in urban cities. These cannot be a reality if there is no energy because the main source of energy is fossil fuel.

As development progresses, tremendous amount of energy is required. Scientists investigated into the petroleum storage beneath the earth crust and estimated that the currently known petroleum supply is estimated to be fully depleted in less than 50 years based on current rate of consumption, provided no further discovery of petroleum reserve (Saidur et. al., 2011). It means almost everything in

our lives, including transportation, food harvesting and processing and industries will be paralysed because they rely heavily on fossil fuel. The fuel crisis has caused concern about the present fossil fuel consumption. Although the current natural gas and coal reserves will sustain for longer period of time, they will still finish soon in the future. Furthermore, the price hike of petroleum in year 2007 and 2008 had given warning to people regarding the future scenario of the world when the fossil fuel approaches its depletion. Hence, petroleum companies are putting efforts to discover new petroleum reserves.

Research in alternative energy such as hydro, geothermal, wave, wind, solar and alternative fuels has started since middle of last century. But they were not progressively done because of abundant supply of fossil fuel. People were not enlightened and the awareness of the fossil fuel depletion is very low due to cheap fuel price. Furthermore, little amount of funding was available for research in alternative fuel as the crisis was not treated seriously. Nevertheless, scientific reports on fuel crisis and recent issue of crude oil price hike have awakened the people to seriously look into the research for alternative energy. Research on alternative fuels has been resumed progressively as both governments and people realise the importance to continue research in renewable fuel supply. Alternative fuels include hydrogen, biodiesel, bioethanol, biogas and producer gas. This includes also the controversial use of nuclear energy.

Hydrogen is a highly explosive and reactive gas. It can be produced in abundant amount via electrolysis of water. Thus, it is believed to have great potential to be the most sustainable fuel provided the production of hydrogen gas can be carried out economically. Moreover, it can be the most environmental friendly fuel because it does not contribute to emission of pollution gases. Investigations have

been done for separation of hydrogen molecules from water molecules. However, a lot of electrical energy is needed for the production of hydrogen from water, which creates problem on the economical and sustainability aspects. Fuel cell technology for hydrogen energy is a new idea that sees the potential of solving the problem. But the rate of production, efficiency and cost are the major obstacle in the research that deprives commercialisation of hydrogen fuel cell. Some researches are also done to convert hydrogen gas from natural gas and liquefied petroleum gas (LPG). However, this is of minimal interest by most researchers as it uses fossil fuel as the raw material.

Other than that, biodiesel and bioethanol are two alternative fuels under research. Bioethanol has already been used by the US and Brazil to be mixed with petrol (gasoline). Bioethanol is produced through fermentation of plants and cellulose (usually using sugarcane) whereas biodiesel is produced by extracting oil from crop, such as oil palm, corn and oil cropping plants. The researches in both fuels show that biodiesel and bioethanol have very good potential to become alternative fuel. However, they are using plants as the raw material, especially food crops. As the amount of fuel needed is huge, therefore is not realistic to use food crop for the purpose. Some people worry that mass production of biodiesel and bioethanol will result in food shortage. New technology of using waste oil to produce biodiesel and using cellulose (wood, plant) to produce bioethanol have been introduced in some countries like Japan. However, currently it involves a lot of energy in treatment and production.

Biogas is rather popular in countries involving actively in agricultural business such as India and China. Agricultural waste and animal manure can be kept

in closed compartments to produce biogas. Methane and ethane are the gases that are usually produced in the process.

Producer gas is another alternative in the list of research. Producer gas or syngas is produced from biomass gasification (Panwar, 2011). Biomass gasification is a thermo-chemical process that produces combustible gas through destructive endothermic decomposition of biomass waste (Basu, 2010). Usually the decomposition process is done by partial combustion in a gasifier with very limited amount of air or more specifically limited amount of oxygen. The biomass used can be wood block, wood chip, sawdust and bark from industrial waste. Furthermore, agricultural residue such as straw from grains, rice husk, coconut, coffee, stalks, verge grass, bagasse and oil palm fibre waste are also sources of raw material for gasification (Basu, 2010). Therefore, biomass gasification utilises plant waste in gasification process, by turning waste into useful energy. Different biomass material used in gasification may result in different percentage of the composition in the producer gas.

Biomass gasification occurs in a reactor called gasifier. There are 4 major types of gasifier that are commonly used to produce producer gas, namely updraft, downdraft, crossdraft and fluidized bed (Reed et. al., 1988). Each of the gasifier has its own characteristics and functions depending on their capability. Therefore, different biomass materials may require different gasifier for optimal function. Biomass with larger size is suitable for the updraft and downdraft gasifier which are the fixed bed gasifiers. On the other hand, biomass with smaller size, often in the form of powder or sludge is used in fluidised bed gasifier (Basu, 2010). In recent years, new technologies have been discovered to improve the heating value of the producer gas, such as the introduction of steam gasification. Steam gasification is a

gasification process carried out with addition of superheated steam (Okajima, 2011). Steam gasification may increase the heating value of producer gas because $H_2$ composition increases noticeably (Lv et. al., 2007). It was proven that with the existence of superheated steam, it will yield more hydrogen as well as carbon monoxide (CO). Hence, producer gas is highly potential to become an alternative fuel for a variety of equipment. Therefore, development of producer gas fueled equipment is essential.

Apart from discovering all sorts of alternatives, another way to conserve fossil fuel is to reduce fuel consumption with equipment having higher efficiency. In combustion technology, lean combustion is a way to increase thermal efficiency of engine or burner (Shinoda et. al., 2002). The concept is to produce less unburnt hydrocarbon at the exhaust and provide a more effective heat transfer medium. Consequently, the technology of increasing efficiency helps in the development of equipment fueled by alternative fuel that has low calorific value, such as producer gas especially in the study of burner design.

Furnace and boiler in most industries use burner or combustor to produce steam and hot gas. Huge amount of coal and diesel are used in the factory operation. So, there is a need to study burner that is capable of burning producer gas efficiently. Producer gas normally has calorific value within the range of 4-5 $MJkg^{-1}$ consisting of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen (Monteiro et. al., 2011). Due to low-calorific-value of producer gas, it is not able to be burnt efficiently in conventional burner.

Burning leaner fuel increases the thermal efficiency of the burner and also reduces the emission of CO, $NO_x$ and unburnt fuel considerably (Shinoda et. al., 2002). Hence, producer gas that has low calorific value can be well related to lean

combustion of fuel with high calorific value. It is highly possible that the combustion of producer gas will give similar encouraging outcome.

Since there is still limited research done in burner design for producer gas, it is crucial to develop a new burner. Hence, porous media burner (PMB) is proposed in this research and compared to a cyclone burner (CB).

## 1.2 Problem statement

As producer gas from the system has very low-calorific-value of about 4-5 MJ $m^{-3}$, it is difficult to be used in conventional burner (Al-Hammarre et. al., 2006). This is because producer gas has very narrow combustion limit for the conventional jet burner. Hence, it is difficult to obtain steady flame. Producer gas consists of CO which has burning velocity at about 9 $cms^{-1}$. Low burning velocity requires long residence time for complete combustion. Conventional burners are designed for gaseous fuel with high burning velocity and burns rapidly requiring less residence time. Other than that, burners fueled by fossil fuel often have the problem of high emission of $NO_x$ and CO.

PMB is one of the popular researches that have been investigated recently. However, most PMB research concentrates on the use of ceramic foam as porous media. PMB inserted with ceramic foam requires periodic maintenance as a result of thermal and mechanical shock from intense combustion (Bakry, 2008). As porous media are often brittle in its nature, long term operation of PMB results in material fatigue that causes destruction of porous media. Replacement of porous foam involves a lot of inconvenience to the whole system, especially when catastrophic failure occurs. It incurs excessive cost of new porous foam and labour charge for maintenance. However, packed bed consists of ceramic balls that are stacked

together to form a bed of porous media. The alumina balls are the commonly used ceramic balls because it has higher thermal and mechanical resistance. Therefore, maintenance cost is much lower due to better reliability. Investigation of alumina balls packed bed PMB was studied with 2.5 mm and 5.6 mm balls fueled by methane (Bubnovich et. al., 2010). However, the PMB is studied for micro-scale burner with 38 mm diameter. Setup with larger diameter of PMB is yet to be discovered.

There is no study done on the combustion of 2-section packed bed PMB using producer gas. PMB investigation was reported for low-calorific-value gas from landfill and simulation gas which has controllable composition of fuel mixture components using porous foam (Al-Hammarre et. al., 2006). But investigation on the performance of burner fuelled by producer gas directly from gasification has not been reported in any literature.

Cyclone burner (CB) is also an efficient device to burn producer gas (Al-Attab et. al., 2011). There is no comparison of characteristics performance between PMB and cyclone burner.

**1.3 Objective:**

The objectives of the study include design, performance and comparison of PMB. The following are the objectives of the study:

1. To investigate the effect of equivalence ratio and second layer packed bed height of porous media burner on temperature profile in the PMB and emissions of CO and $NO_x$ at the exhaust of PMB.
2. To compare the performance of PMB and CB in terms of temperature profile and emissions of CO and $NO_x$.

3. To incorporate a hot air generation system to determine the PMB heat output, efficiencies and effectiveness.

### 1.4 Scope of work

1. In the research, a two-layer porous media burner is to be developed. The first and second layers consist of 10 mm and 20 mm alumina balls respectively. Both layers of alumina balls form packed bed in the PMB. The parameters to be studied include equivalence ratio and height of second layer packed bed.
2. The study will be done to investigate the temperature profile as well as CO and $NO_x$ emissions of the PMB under submerged combustion mode in variation with the parameters investigated.
3. The research concentrates on premixed combustion of producer gas in the PMB.
4. The producer gas is produced from a throatless stratified downdraft gasifier fueled by wood chip. Air is mixed with the producer gas prior to the burner.
5. A cyclone burner with identical dimension as the PMB will be studied for the same parameters and desired output.
6. The performance of PMB will be compared to the cyclone burner with the producer gas output from the same gasifier fueled by wood chip.
7. Subsequently, the best condition of the second layer packed bed height of PMB will be determined based on the highest temperature in the PMB and lowest emission. The lean limit and rich limit of the PMB at the particular second layer packed bed height will be determined.
8. In addition to that, the chosen height of second layer packed bed will then used for investigating the heat output from a shell and tube heat exchanger that is incorporated with the PMB. Heat output, overall system efficiency, PMB-heat

exchanger efficiency and effectiveness of heat exchanger will be studied with varying equivalence ratios.

### 1.5 Thesis outline

This thesis starts with a brief introduction on the background, problem statement and objectives of the study. It is followed by an introduction to the biomass gasification system and a review of PMB in Chapter 2. Subsequently, Chapter 3 elaborates the methodology used to carry out the investigation. Design of PMB, procedure of experiment and details of equipment used are introduced. Then, the results from the research are presented and discussed in Chapter 4. Conclusions drawn from the study are stated in Chapter 5 with recommendations for future work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Biomass As Renewable Energy Sources

The use of renewable energy sources become increasingly necessary nowadays, due to the need to achieve the changes required to address the impacts of global warming. Renewable energy is of growing importance in satisfying environmental concerns over fossil fuel usage. Wood and other forms of biomass including energy crops, agricultural and forestry wastes are some of the major resources available for renewable energy. Lately, much attention has been focused on identifying suitable biomass species, which can provide high energy outputs, to replace conventional fossil fuel that is soon depleted.

Human being had started exploiting biomass resources for generating energy since the ancient times. The discovery of fossil fuel results in the invention of engines that develops the transportation system as well as generating electricity. More recently, fossilised biomass has also been researched such as coal and crude oil. However, the conversion of biomass into fossil compound takes millions of years that it is not renewable within a time-scale mankind can use (Mann et. al., 2009). The continuous uncontrolled consumption of fossil fuel will eventually deplete the non-renewable resources. Burning new biomass that is currently available contributes no net carbon dioxide addition to the atmosphere, because replanting harvested biomass consumes more carbon dioxide through photosynthesis: a balanced carbon dioxide cycle is achieved. Therefore, the use of biomass energy has the advantages of less

utilisation of non-renewable energy resources and contributed to zero carbon dioxide addition to the environment.

## 2.2 Biomass

In the context of energy production through biomass, it is often meant by plant based material. Biomass is the plant material derived from the reaction between $CO_2$ in the air, water and sunlight, via photosynthesis, to produce carbohydrates that form the basic structure of biomass. Biomass is carbon based compound which composed of a mixture of organic molecules containing hydrogen, usually includes atoms of oxygen, often nitrogen and also small quantities of other elements, including alkali, alkaline earth and heavy metals. There are various types of biomass resources available. As for plant based materials, it can be mainly categorised into four main types of biomass (McKendry, 2002):

- Woody plants
- Herbaceous plants/grasses
- Aquatic plants
- Manures

## 2.3 Conversion of Biomass to Energy Sources

Biomass fuels and residues can be converted to energy via thermal, biological and physical processes. In the thermochemical conversion technologies, there are three main thermal processes available for converting biomass to useful energy form, namely pyrolysis, gasification and combustion. Their products and applications are summarised in Figure 2.1 (Rosentrater et. al., 2006).

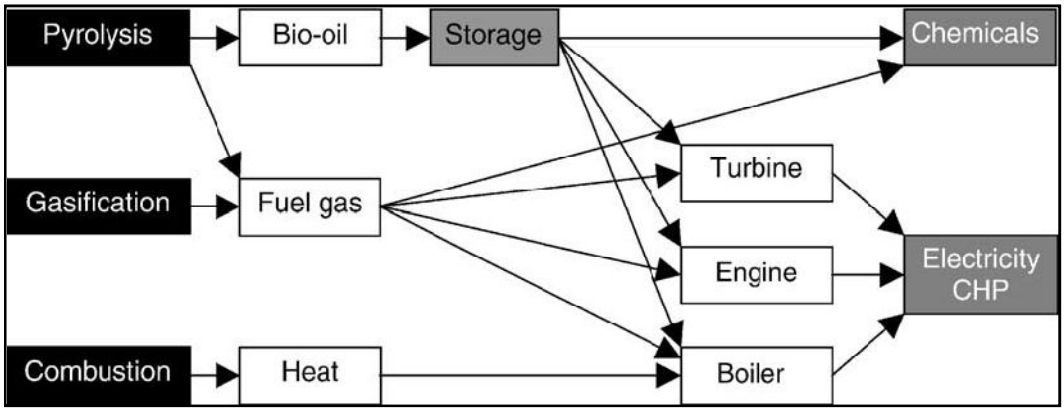


Figure 2.1: Products from biomass conversion

## 2.4 Biomass Gasification

As the utilisation of biomass does not contribute to net carbon dioxide increase in the atmosphere, biomass gasification technology is a feasible approach for environmental friendly applications. This is parallel to the call for environmental awareness throughout the world. Since there are huge amount of plant waste from all different sources, it can be a potential substitute to fossil fuel.

Biomass gasification is an endothermic conversion process that converts organic carbonaceous materials into burnable gaseous products through partial oxidation of the materials at high temperatures under controlled amount of oxygen and/or steam (Basu, 2010). The resulting gas mixture is combustible gaseous fuel often called with several different names: producer gas, synthesis gas (syngas) or wood gas. In short, biomass gasification is a method for extracting energy from different types of organic materials. The main constituents of producer gas are hydrogen ($H_2$), carbon monoxide (CO), methane ($CH_4$), carbon dioxide ($CO_2$), nitrogen ($N_2$), water vapour ($H_2O$) and small amount of oxygen and other hydrocarbons (Basu, 2010). Biomass gasification uses air as gasifying agent, hence it produces producer gas with rather low calorific value ranges from 4-6 $MJm^{-3}$. The

reason of very low calorific value is partly due to nitrogen dilution. However, much higher calorific value in the range 10-20 $MJm^{-3}$ can be obtained by using oxygen and steam gasification process to yield higher concentration of hydrogen and carbon monoxide as nitrogen dilution is avoided (Matsuoka et. al., 2008). But the concern is the requirement of external energy to produce compressed oxygen gas and superheated steam.

The advantage of biomass gasification is the more efficient utilisation of solid fuel compared to direct combustion. Producer gas can be burnt directly in internal combustion engines, provided with proper gas cleaning to eliminate tar and particles present in the gas. Biomass gasification is also suitable for materials that are not otherwise useful fuels, such as organic waste and animal manures. In short, almost any type of organic material can be used as the raw material for gasification.

### 2.4.1 Basic Processes of Gasification

The entire gasification procedure basically consists of four processes: drying, pyrolysis, combustion and reduction. (Reed et. al., 1988) Different gasifier designs result in different distribution of the region of the four processes.

During drying process, surface moisture and cell bound water are removed from the biomass by evaporation. These processes ideally take place at a temperature up to about 160ºC. The water vapour will flow downwards and add to the water vapour formed in the oxidation which is undesired.

In pyrolysis zone, biomass is subjected to high temperatures in the absence of oxygen resulting in the production of oil, char or volatile. The volatiles consist of non-condensable vapours (e.g. methane, carbon-monoxide) and condensable vapours (various tar compounds). The process transforms the biomass into high quality fuel

without creating ash or energy directly. In pyrolysis process, biomass feedstock is decomposed endothermically by heat at about 500$^{o}$C. Devolatilisation occurs and yields 75-90% of volatile products in both gaseous and liquid form. High carbon content material such as char will be remained as it is non-volatile (Goswami, 1986).

Part of the carbon and volatile are burnt to provide heat for the previously described processes in the oxidation/combustion zone. An important function of the oxidation zone, apart from heat generation, is to convert and oxidize virtually all condensable products from the pyrolysis zone. In order to avoid cold spots in the oxidation zone, air inlet velocities and the reactor geometry must be well controlled.

In the reduction zone, the sensible heat of the gases and charcoal is converted as much as possible into chemical energy of the producer gas. The end product of the chemical reactions that take place in the reduction zone is a combustible gas which can be used as fuel gas in burners.

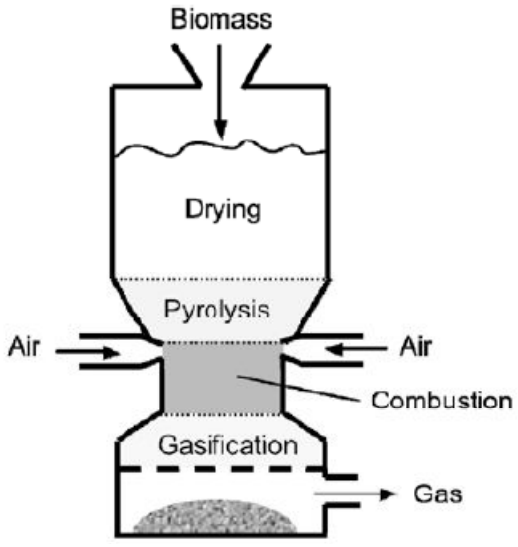


Figure 2.2: Process of gasification (Basu, 2010)

### 2.4.2 Major Reactions in Gasifier

The reaction in combustion zone is exothermic that results in high temperature of over 1000°C. The two major reactions are (Basu, 2010):

$$C + O_2 \rightarrow CO_2$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

Subsequently, the gas product, including remaining char, carbon dioxide and water vapour flow through the reduction zone where the endothermic reactions take place forming carbon monoxide, hydrogen and other combustible gases.

$$C + CO_2 \rightarrow 2CO$$

$$C + H_2O \rightarrow CO + H_2$$

$$CO + H_2O \rightarrow CO + H_2$$

$$C + 2H_2 \rightarrow CH_4$$

$$CO_2 + H_2 \rightarrow CO + H_2O$$

The first two reactions are the major endothermic reactions in the reduction zone. Temperature in the reduction zone is lower than combustion zone as the endothermic reactions absorb heat from the combustion zone. Also, the quality of producer gas increases as temperature is reduced. This is because more combustible species are produced and the calorific value of producer gas increases. The reduction zone usually has temperature of between 800°C and 900°C (Basu, 2010).

## 2.5 Type of Gasifiers

Gasifiers are different in terms of their designs, suitability for feedstock, range of capacity and applications. Gasifiers can be categorised into 3 major categories, namely, fluidised bed gasifier, moving/fixed bed gasifier and entrained flow gasifier.

### 2.5.1 Fluidised-Bed Gasifier

Fluidised-bed gasifier consists of a bed of granular solids that forms a bed of porous characteristics. Air is passed through an air distribution plate causing the bed materials to exhibit semi-suspended fluidised behaviour that provides excellent mixing of biomass input and thus yield uniform temperature in the gasifier. This is important to reduce problem of fuel agglomeration. There are mainly two configurations of fluidised bed gasifier: bubbling fluidised-bed and circulating fluidised-bed.

In a bubbling fluidised-bed gasifier, selected fine and inert particles with specific size, density and thermal characteristics serve as the fluidising media. Usually, silica sand or alumina is used. The gasifying agent (air, oxygen or steam) is forced through the particles to produce bubbling and channelling of gas through the media.

Circulating fluidised-bed gasifier has similar design and concept as bubbling configuration. The difference is the higher inlet gas velocity compared to the fluidisation velocity in the bubbling fluidised-bed. This causes entrainment of particles in the gas stream which will be separated in a cyclone separator. Also, the bed materials and biomass mixture is circulated back into the gasifier. The bed materials will be circulated back to the main chamber at the bottom.

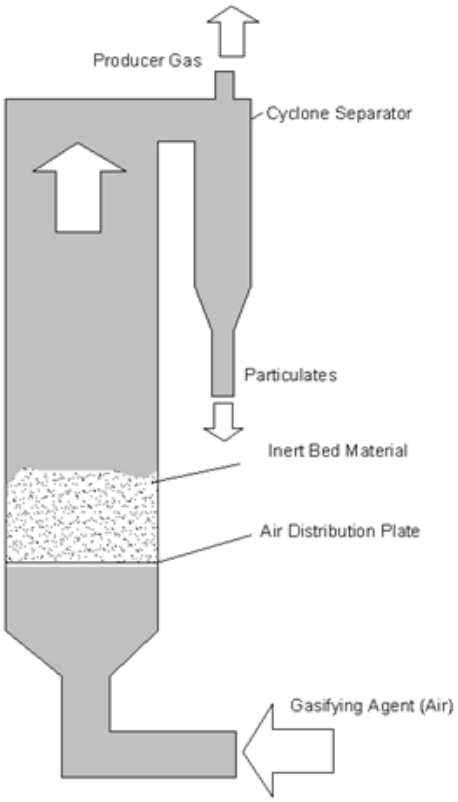


Figure 2.3: Bubbling fluidised-bed gasifier (Lim, 2007)

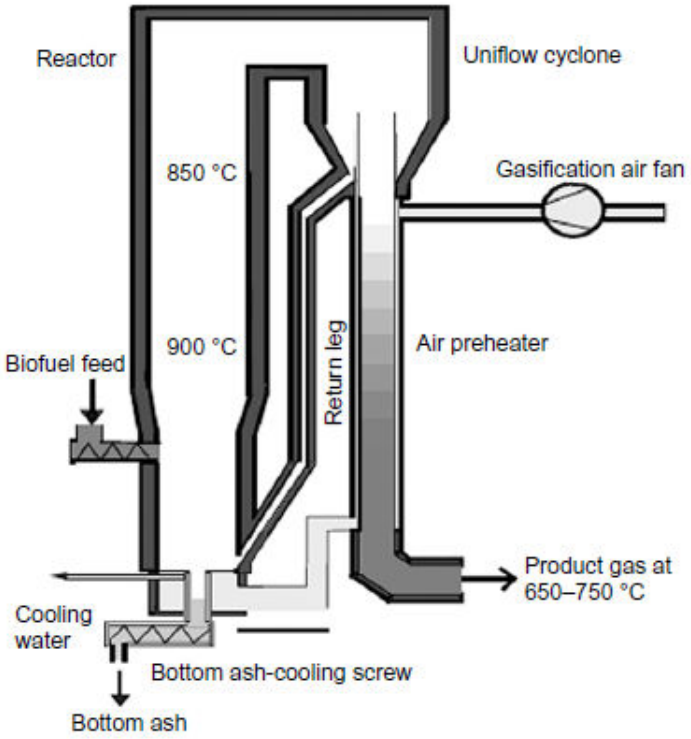


Figure 2.4: Circulating fluidised-bed gasifier (Basu, 2010)

### 2.5.2 Entrained Flow Gasifier

Figure 2.5 shows the schematic diagram of the operating principle of entrained-flow gasifier. Fine biomass particles enter the reactor along with oxygen supply. Devolatilisation of biomass takes place near the entrance zone, where the recirculation of high velocity jet occurs. Combustion of biomass produces high temperature and consumes all the oxygen. Gasification reaction takes place downstream of the gasifier. As the gasification process is slower than the combustion region, hence longer reactor should be designed to yield complete char conversion into gas.

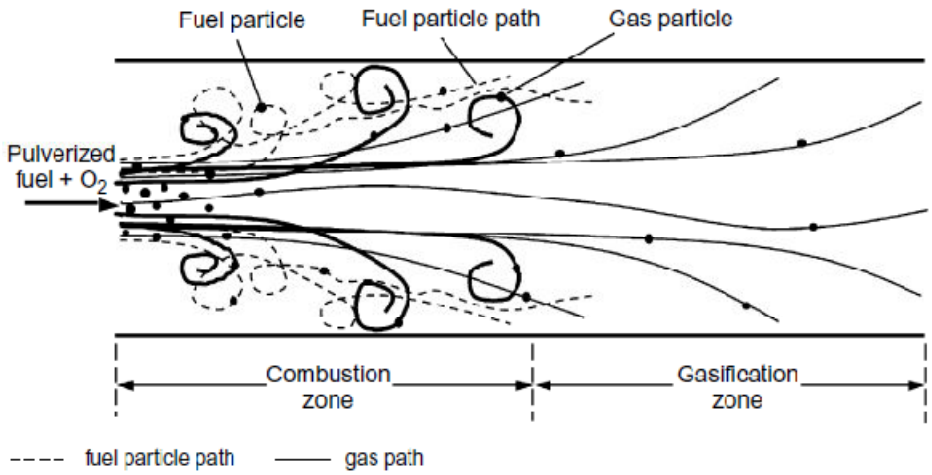


Figure 2.5: Schematic diagram of entrained-flow gasifier

### 2.5.3 Cyclone Gasifier

Cyclone gasifier is used for gasification of fine biomass particles such as sawdust that has size less than 1 mm. It is capable of generating producer gas that is cleaner than that of fluidised bed gasifier. It operates based on the principle of a cyclone separator. But, in the case of cyclone gasifier, biomass is directly fed into the cyclone for combustion and gasification. The cyclonic flow causes the particles to

move to the wall. As the swirling flow approaches the conical part of cyclone, the higher centrifugal force draws gas to the central vertical spiral and ascends to the top of cyclone. The ash and char are separated from the cyclone at the apex of cyclone. The long residence time provided by the swirling flow allows the biomass to have enough time to undergo combustion and gasification (Miskam, 2006). The design of cyclone gasifier is as shown in Figure 2.6.

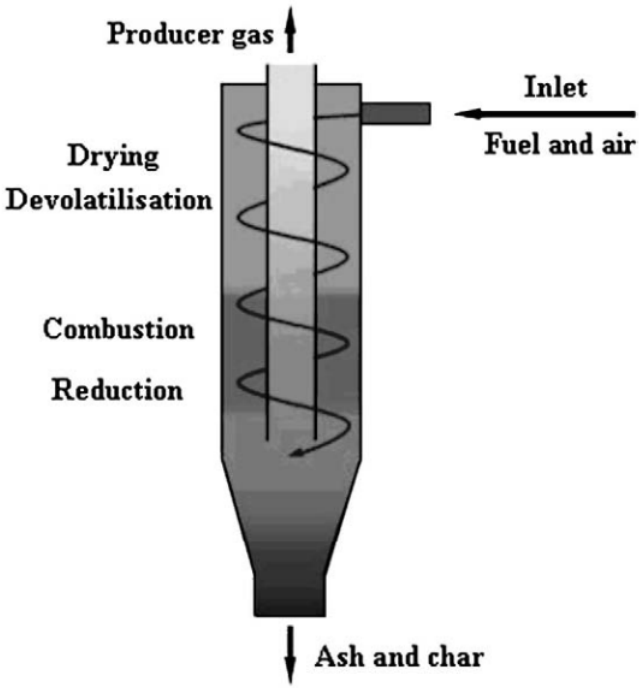


Figure 2.6: Design of a cyclone gasifier (Sun et. al., 2009)

### 2.5.4 Fixed Bed/Moving Bed Gasifier

In a fixed bed gasifier, biomass sits on a grate which forms a bed of fuel on top of the grate. On the other hand, during gasification process, the biomass move downwards as it is consumed. Hence, it is also called moving bed.

Fixed bed gasifiers are suitable for small scale applications whilst fluidised bed gasifiers are more suitable for large scale application. Moreover, fixed bed

gasifiers have the lowest cost of fabrication for small scale applications. Therefore, they are most widely used all around the world. Also, it is suitable for usage of coarse biomass that has larger size, such as wood chip and wood block. Fixed bed gasifiers include updraft gasifier, downdraft gasifier and crossdraft gasifier.

#### 2.5.4.1 Updraft Gasifier

Updraft gasifier is also called counter-flow gasifier. In an updraft gasifier as shown in Figure 2.7, biomass is fed from the top of the reactor, with a grate at the bottom to support the whole reaction zone. Gasifying (oxidising) agent, usually air, is introduced from the bottom, below the grate. Therefore, the char at the bottom of the reactor bed undergoes complete combustion producing $CO_2$ and $H_2O$ under high temperature of about 1000$^{o}$C. The gases pass upwards through the combustion zone to the reduction zone. The gases are reduced to CO and $H_2$. The gases cool down as they move up through the zones. After the reduction process, the CO and $H_2$ at a temperature of about 750$^{o}$C move to the pyrolysis region. Finally, it passes through the drying zone where the heat in the producer gas dries up the biomass at the top. Producer gas, tar and volatiles are released from the top of gasifier (Goswami, 1986). Ashes are removed from the bottom of the gasifier. Since updraft gasifier produces high tar content of about 30% by weight, it is still commonly used with charcoal.

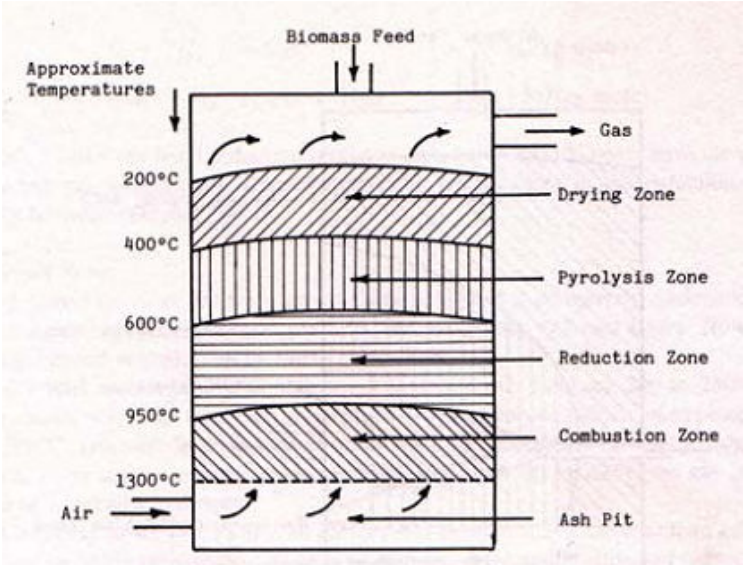


Figure 2.7: Schematic diagram of an updraft gasifier (Reed et. al., 1988)

### 2.5.4.2 Crossdraft Gasifier

In a crossdraft gasifier as shown in Figure 2.8, gasifying agent enters at high velocity through a single nozzle. This produces substantial circulation and creates a flow across the bed of biomass and char. With the design of crossdraft, it can attain very high temperature in a small volume. Therefore, it has fast response time. However, it requires the use of low tar content biomass to avoid bridging and channelling (Goswami, 1986).

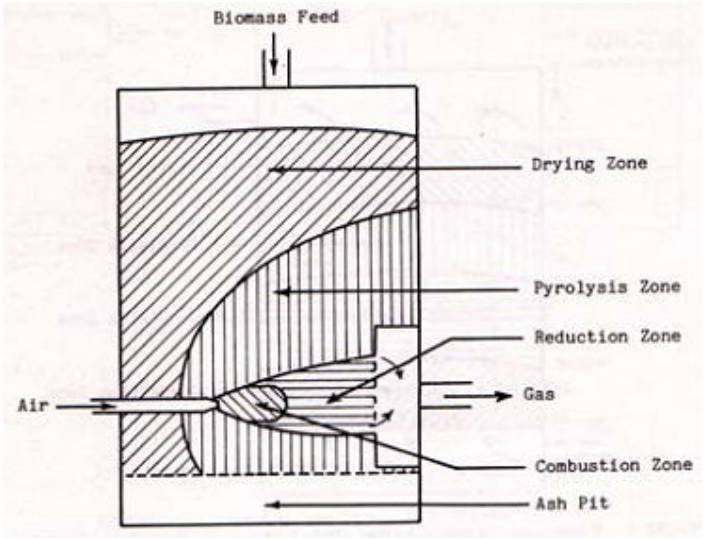


Figure 2.8: Schematic diagram of a crossdraft gasifier (Reed et. al., 1988)

#### 2.5.4.3 Downdraft Gasifier

Downdraft gasifier (Figure 2.9) is sometimes called concurrent-flow gasifier. It has the same mechanical configuration as updraft gasifier. But they are different in term of flow direction of producer gas. Air, as gasifying agent flows in the same direction as the biomass feed and it is channelled directly to the gasification zone. As biomass is fed from the top, it undergoes drying at the top of the gasifier before the pyrolysis zone. The reactions and products of pyrolysis process depend mainly on temperature, as well as pressure and residence time. Between 200$^{o}$C and 280$^{o}$C, carbon dioxide, acid and water vapour are produced. As the temperature rises between 280$^{o}$C and 500$^{o}$C, devolatilisation of biomass occurs with high amount of tar. If the temperature further rises to 700$^{o}$C, most of the biomass turns into volatile material with minimal amount of gases. Then, the volatile materials and gases produced will proceed to the combustion zone. The pyrolysis region is heated by radiation and convection heat from the combustion zone. In the combustion zone, pyrolysed char particles are combusted yielding temperature about 1000$^{o}$C. The volatiles are forced into the combustion zone and causes thermal cracking of the tar. The volatiles then moves to the gasifying zone, where reduction of gas occurs to yield producer gas. The producer gas leaves at the bottom of gasifier and ash drops into ash tank (Basu, 2010).

Low tar production is among the advantages of downdraft gasification because high temperature in the combustion zone enables thermal cracking of tar. The characteristic makes it suitable for engine applications. Also, it requires much shorter time for startup compared to updraft gasifier as it manages to achieve working temperature fast. The drawback is the requirement of low moisture content biomass less than 20% and low limit of fuel shape.

Downdraft gasifier can be divided into two types, namely throatless and throated gasifier. Throatless gasifier is also called open top or stratified throatless gasifier. It has the top opening exposed to atmosphere, permitting continuous feeding of biomass from the top. As shown in Figure 2.9, it provides unrestricted movement of biomass in gasifier, preventing the occurrence of bridging and channelling. Furthermore, it has simple design which makes fabrication easier and cost effective (Basu, 2010).

On the other hand, throated downdraft gasifier possesses constriction which is called a throat at the combustion zone as shown in Figure 2.10. All the pyrolysis products are forced through the high temperature combustion zone that all the tar is cracked. Table 2.1 gives a summary of the characteristics of different fixed/moving bed gasifiers.

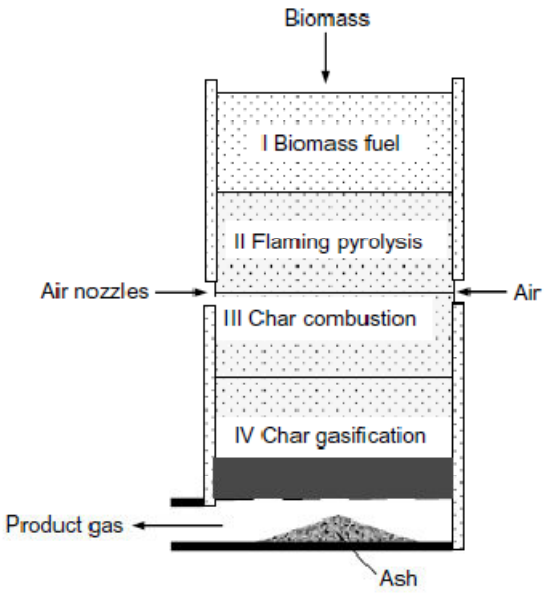


Figure 2.9: Design of throatless gasifier (Basu, 2010)

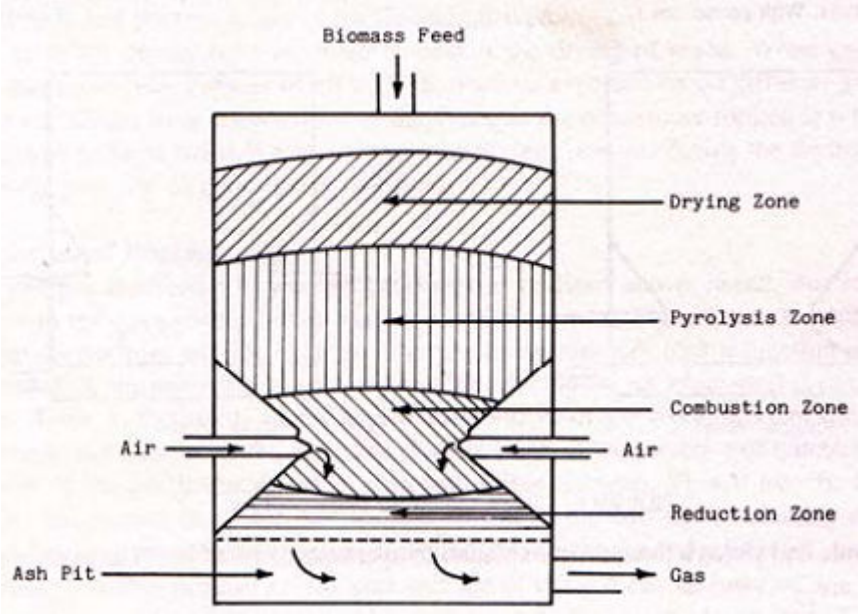


Figure 2.10: Typical throated downdraft gasifier (Reed et. al., 1988)

Table 2.1: Characteristics of fixed/moving bed gasifier (Basu, 2010)

| **Fuel (Wood)** | **Updraft** | **Downdraft** | **Crossdraft** |
|---|---|---|---|
| Moisture wet basis (%) | 60 max | 25 max | 10-20 |
| Dry-ash basis (%) | 25 max | 6 max | 0.5-1.0 |
| Ash melting temperature ($^oC$) | >1000 | >1250 | |
| Size (mm) | 5-100 | 20-100 | 5-20 |
| Application range (MW) | 2-30 | 1-2 | |
| Gas exit temperature ($^oC$) | 200-400 | 700 | 1250 |
| Tar ($g/Nm^3$) | 30-150 | 0.015-3.0 | 0.01-0.1 |
| Gas LHV ($MJ/Nm^3$) | 5-6 | 4.5-5.0 | 4.0-4.5 |
| Hot-gas efficiency (%) | | | |
| Turn-down ratio (-) | 5-10 | 3-4 | 2-3 |
| Hearth load ($MW/m^3$) | <2.8 | | |

## 2.6 Porous Media Burner (PMB) Technology

Porous media burner (PMB) is a technology that inserts porous materials in the combustion zone of a burner. The most common form of porous material used is ceramic. The concept was initially introduced by Weinberg in 1971. The use of ceramic is due to its high heat capacity and its capability of withstanding high temperature combustion that leads to good resistance to thermal shock (Wood et. al., 2008). As porous foam contains pores within the solid, it allows movement of fluid through the porous foam. In early development of PMB technology, porous media are used as medium for heat transfer from the exhaust to the incoming air and fuel for preheating purpose (Wood et. al., 2008). It is later designed to serve as a medium for fuel combustion. Therefore the selection of porous material with the suitable properties is crucial in the burner design. Other than that, PMB is capable of operating over a wide range of operating condition, including combustion under ultra lean condition (Kamal et. al., 2006). PMB is capable of sustaining methane combustion with equivalence ratio as low as 0.14 (Xie et. al., 2009). This ultra-lean burning condition allows combustion of low-calorific-value gaseous fuel that is unable to be combusted well in conventional burner hence increases the combustion efficiency of low-calorific-value gaseous fuel, allowing the exploitation of all kinds of fuel. Exhaust gas from a turbine is reburnt in a PMB to utilise unburnt gas (Shinoda et. al., 2002, Wood et. al., 2008). Consequently, the extended flammability limit in PMB also means PMB manages to operate with higher mixture inlet velocity compared to conventional burner.

The operating principle of PMB is based on several concepts that are put forward by some researchers previously. First and foremost, it is the excess enthalpy concept that covers the whole mechanism of porous media combustion technology.